Modem Basics

GENERAL INFORMATION

The **modem** or **mod**ulator/**dem**odulator serves as the interconnecting link for digital equipment to communicate over telephone or other wire media. As shown in Figure 1 the modem encodes (modulates) incoming binary data into signals suited for transmission over the available media.

Conversely on the opposite end, the other modem decodes (demodulates) the received signals from the line. In this figure, Rxd_2 (received data) would be identical to that of Txd_1 and Rxd_1 equal to Txd_2. That is a properly operating modem receiving an encoded signal would reproduce at its output exactly what the transmitting modem had at its Txd input. The modem initiating the "conversation" is termed the **originate** and the receive modem the **answer**. Figure 1 illustrates modems which have the ability to communicate both directions, which when able to do simultaneously is known as **full-duplex** operation. This same communication in both directions but only one direction at a time is **half-duplex** operation. Communication in only one direction is **simplex** operation. These modes of operation can be likened to a television for simplex, a CB which has to be keyed to talk for half duplex and a telephone for full duplex where both parties can talk at once.

Modem speeds of transmitting and receiving are specified in **BPS** (bits per second). This term describes the number of binary data bits that can be transmitted per second. For low speed modems, **baud rate** is interchangeably used in place of BPS. **Low** speed modems are usually those with 0 to 1200 BPS, **medium** speed for 2400 to 9600 BPS, and those above 9600 BPS **high** speed. Most modems are generally classified according to which **Bell** (US) or **CCITT** (European) standard they conform to. This standard indicates the modem speed, operation and encoding technique used. Figure 2 shows the most popular low and medium speed standards used.

MODULATION TECHNIQUES

Many types of encoding formates are used in modems, with the speed of the modem and type of media usually the determining factors. Here the two most popular will be discussed, FSK and PSK.

FSK or frequency shift keying, illustrated in Figure 2, encodes binary data into two discrete frequencies.

STANDARD	SPEED	OPERATION	ENCODING TECHNIQUE
103	0-300 BPS	Full-Duplex	FSK
201	1200 BPS	Half-Duplex	PSK
202	1200 BPS	Half-Duplex	FSK
212A	0-300	Full-Duplex	FSK
	1200		PSK
	(A)		
V.21	0-300 BPS	Full-Duplex	FSK
V.22	1200 BPS	Full-Duplex	PSK
V.23	1200 BPS 75 BPS	Half-Duplex	FSK
V.26	2400 BPS	Half-Duplex	PSK
	(B)		

Figure 2: Popular Bell (A) and CCITT (B) Standards

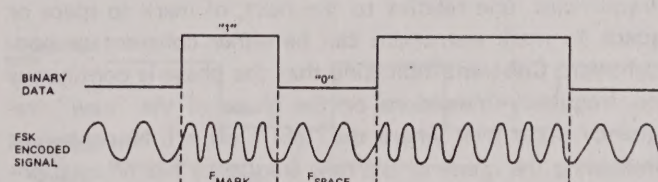

Figure 3: FSK Encoding

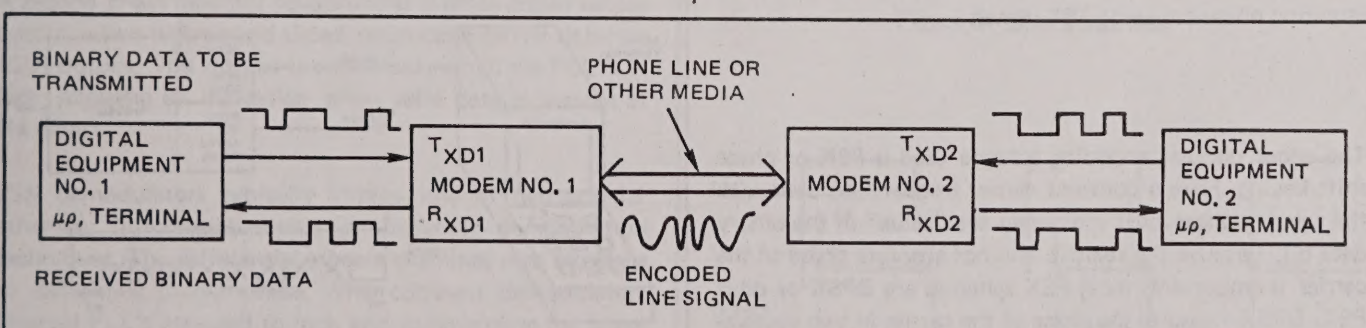

Figure 1: Modem System Block Diagram

The pair of frequencies used in the FSK scheme are chosen to be within the bandwidth of the media used. For example; the telephone line has a bandpass characteristic with the low frequency cutoff of about 300 Hz and a high frequency cutoff of about 3 kHz. For the telephone line the FSK frequencies would have to both fall within it's 300 Hz to 3 kHz frequency restriction. With the FSK scheme the higher frequency is known as the **mark** frequency and the lower the **Space.** The placing of the frequencies, as mentioned, strongly depends on the media bandwidth, however, the spacing between the mark and space frequencies also depends on the demodulation techniques used. For PLL (Phase-Locked Loop), demodulation, described in subsequent sections, the following relationships must be met:

A. For wide mark-space deviations (close to 2 to 1)

$$f_{mark} - f_{space} = \Delta f \geqslant \text{baud rate (BPS)} \times .83$$

B. For narrow spacing

$$f_{mark} - f_{space} = \Delta f \geqslant \text{baud rate (BPS)} \times .67$$

In full–duplex systems two mark/space frequency pairs must be used, one for answer mode and another for originate. This is necessary because of the simultaneous two way communication for full–duplex operation. The phase of the frequencies, one relative to the next, of mark to space or space to mark transitions can be either coherent or noncoherent. **Coherent** indicating that the phase is continuous on frequency transitions or the phase of the "new" frequency takes over where the "old" left off. **Noncoherent** indicating the phase of the new frequency has no relationship to that of the old. Here again the demodulation technique used being the determining factor of the necessity of phase coherency. PLL demodulation is one popular scheme requiring phase coherent FSK signals.

The other popular encoding scheme used is **PSK** or phase shift keying. Here a constant carrier frequency is used with the relative phase of it indicating the "value" of the binary data bit. Because the relative and not absolute phase of the carrier is important, most PSK schemes are **DPSK** or dibit PSK. DPSK measures the phase of the carrier in two successive bit frames in order to determine the phase change. Figure 4 illustrates PSK encoding, with Figure 5 listing the phase shifts and dibit values for two popular PSK modems.

PSK operates in either **SYNC** (synchronis) or **ASYN** (asynchronis) formats. Sync systems use a transmit clock from the digital equipment to clock data out and maintain synchronization. In this format the data stream itself has no synchronizing information. In ASYNC systems, there is no timing signal from the digital equipment to the modem. Here synchronization and timing information is derived from start and stop bits placed in the data stream bracketing each character. Timing is maintained by the modem inserting or removing stop bits. Figure 6 illustrates a terminal connected to a SYNC system in (A) and ASYNC system in (B).

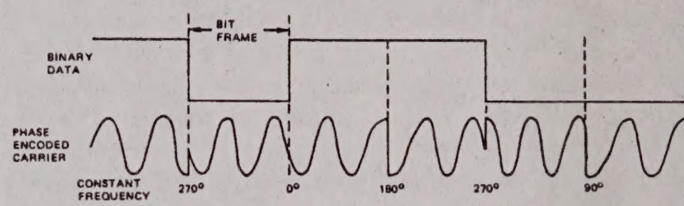

Figure 4: PSK Encoding

STANDARD	**BELL 212A/V.22**				**BELL 201/V.26**			
Phase Shift	0°	+90°	-90°	+180°	45°	135°	225°	315°
Dibit Value	01	00	11	10	00	01	11	10

Figure 5: Popular Phase Shifts and Dibit Values

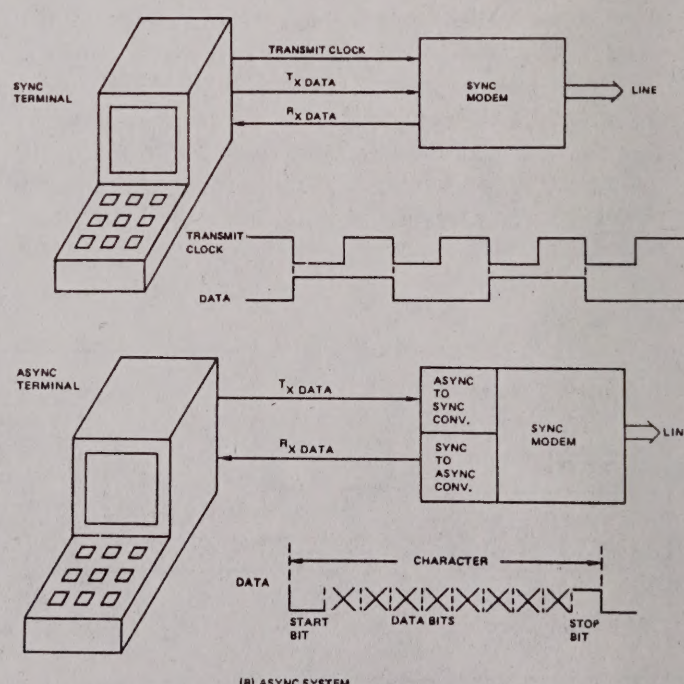

Figure 6: SYNC and ASYNC Formats

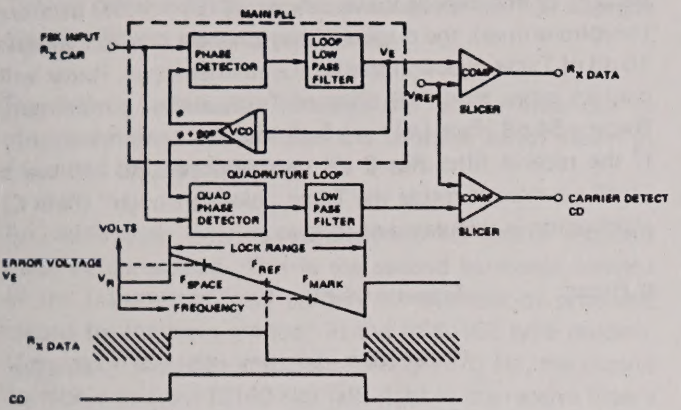

Figure 7

Different character lengths are used, with Bell 212A having options for 9 or 10 bit lengths, or 7 or 8 data bits each with one start and one stop bit.

DEMODULATION TECHNIQUES

Once data has been encoded onto a carrier, Txcar, by the modulator in either FSK or PSK formats, the receiving modem (answer mode) must decode or demodulate this received carrier, Rxcar. For FSK encoding, analog and digital techniques are used for demodulation. Popular analog schemes often imploy PLL type demodulation. Using this method, illustrated in Figure 7, a PLL locks to the incoming FSK frequencies and produces two different DC error voltages at the phase detector output. These voltages are compared to a reference to indicate whether the incoming frequencies lie above or below a reference frequency, or whether they are mark (high) or space (low) frequencies.

A second phase detector (quadruture) is often added whose output, when filtered and sliced, produces a carrier detector (**CD**) output. This output is active only when the PLL is in lock, allowing an indication when valid data is present at Rx data.

PSK demodulators typically imploy one of two popular schemes, differential digital or coherent demodulation techniques. The differential scheme examines zero crossings to determine carrier phase. With coherent demodulators internal PLL's are used to lock and to determine the phase of the incoming carrier. Coherent schemes usually provide better overall performance, but at the sacrifice of higher circuit complexity and cost.

The demodulator affects and determines several key parameters of the modem. The demodulation process adds several degradations to the other originally transmitted data. One, **Bias distortion**, illustrated in Figure 8, is easiest seen in an alternating 0,1,0,1. . . data pattern. This pattern should have equal times for each bit, high (1) and low (0) ($T_{1t} = T_{ot}$).

Bias distortion describes how far from equal the received data, Rx_{data}, high and low times are:

$$\text{Bias distortion (\%)} = \left[.5 - \frac{T1RX}{T1PX + T0RX}\right] 100$$

Output jitter is another parameter describing the quality of the demodulation process. Illustrated in Figure 9 again with an alternating 0,1,0,1. . . data pattern.

The output jitter is usually specified in percent, indicating what percentage of the bit frame the peak to peak jitter is.

$$\text{Jitter (\%)} = \left[\frac{\text{Tmaximum} - \text{Tminimum}}{T_b}\right] 100$$

FILTER REQUIREMENTS

Filters in modems serve two functions; to filter the modulator output for band limiting and filtering of the received carrier (Rxcar) before the demodulator. Figure 10 illustrates these filter functions.

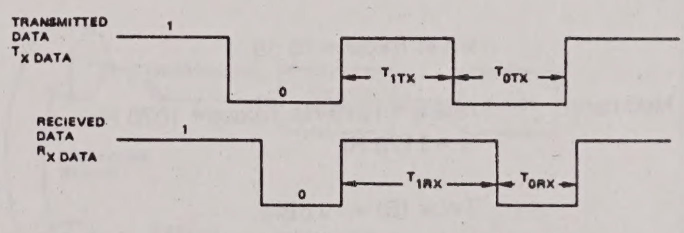

Figure 8: Bias Distortion

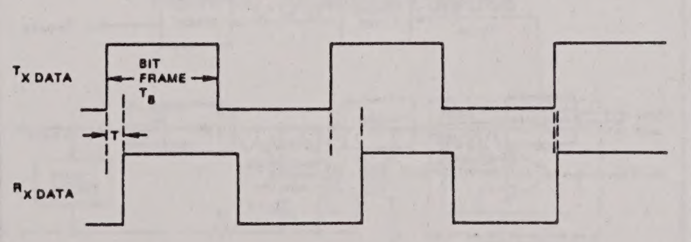

Figure 9

The transmit filter is typically a lowpass or bandpass structure. As this filter is used to bandlimit the modulated carrier, it is usually of low order (low number of poles to zeros). The complexity is defined by the frequency spectrum generated by the modulator and how well this has to be confined on the media. For example; telephone lines have restrictions as to the amplitude of frequency even above its narrow 3 kHz band width (see FCC requirements).

The receive filter serves two functions: remove noise from the received signal and more importantly remove any local modulator signal which gets mixed with the receiver carrier. Figure 11 illustrates the function of the receive filter.

An additional block (duplexer) must be considered when specifying the receive filter. The duplexer acts to channel the received carrier from the media to the demodulator, A, and channel the transmit carrier to the media, B (four to two wire conversion). Imperfections in the duplexer allow some of the Txcar to get into the Rxcar, C. Therefore, to maintain a good **S/N** (signal to noise) ratio at the demodulator input, Rxcar, the receive filter must remove this unwanted local Txcar. An example illustrates the consideration in terminating the complexity of the receive filter. In this case, an FSK, Bell 103 Type, modem is examined, as shown in Figure 11, with the following requirements:

Demodulator: fmark = 2225 Hz; fspace = 2025 Hz,

$$fc = \frac{2225\text{Hz} - 2025\text{ Hz}}{2} = 2125\text{ Hz}$$

Rxcar dynamic range = - 10 dBm to -48 dBm

s/n at Rxcar = 15 dB

Modulator: fmark = 1270 Hz, fspace = 1070 Hz, fc = 1170 Hz

Txcar (B) = -9 dBm

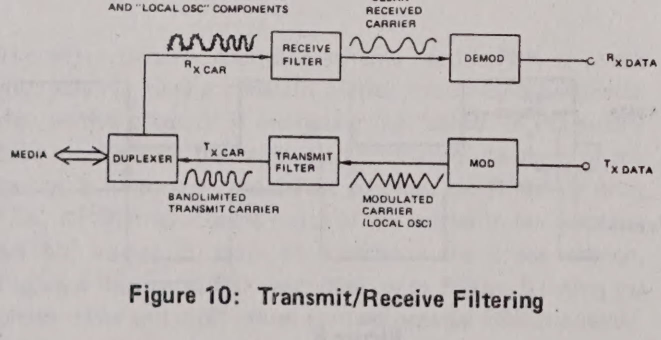

Figure 10: Transmit/Receive Filtering

Because of line impedance variations, 600Ω ± 100Ω or more (telephone lines), the duplexer may only be able to maintain 10 dB of Txcar rejection to the receive filter input. Rxcar will contain more than -19 dBm of Txcar and at a minimum, Rxcar = 54 dB [Path (A) has a 6 dB loss due to termination]. If the receive filter has 0 dB passband gain, to achieve a 15 dB s/n ratio at Rxcar the Txcar "bleed through" (Path C) attenuation is calculated as follows:

at Rxcar: Signal = 54 dBm

Txcar (C) = -54 dBm - 15 dBm = -69 dBm

Attenuation = -10 dBm - (-69 dBm) = 50 dB

The filter requirements are illustrated in Figure 12.

Other requirements to consider are filter bandwidth, which optimally is set close to the FSK baud rate, or here 300 Hz (small bandwidths can alter the transmitted carrier's spectrum). The phase response or specifically group delay within the passband can degrade the quality of the Rx data in terms of jitter. The **group delay (GD)** is a measure of the difference in time it takes for a mark or space frequency to pass through the filter. It is calculated by taking the first derivative of phase, with respect to frequency:

$$GD = \frac{d\theta}{df}$$

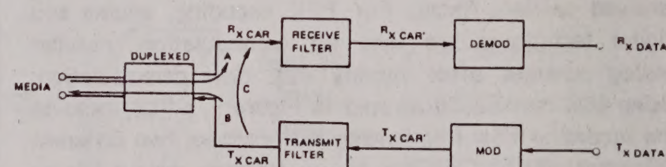

Figure 11: Modem Signal Paths

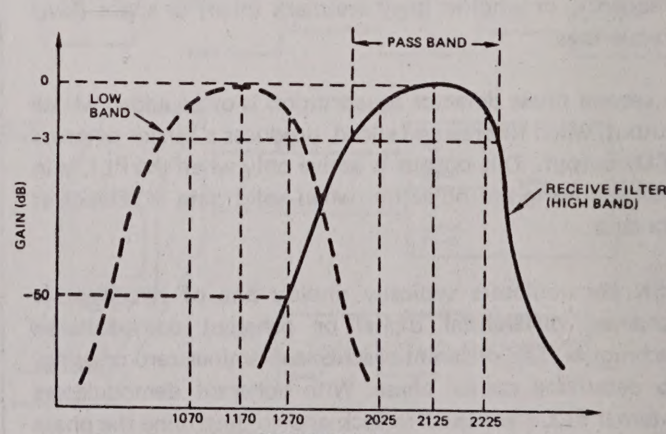

Figure 12: 103 FSK Receive Filter.

Typical differential group delay values for the 103 example are 50 - 300 us over the pass band.

For full or half-duplex modems the receive filter can be used for transmit filtering of the opposite band, shown in Figure 13 (mode switching).

An additional filtering requirement for many modems must be considered. This is the second harmonic content of the transmitted local carrier. An example of problems caused by the term are seen in the FSK 103 type modem. If the local modulator is transmitting 1070 Hz, the second harmonic content (2140 Hz) falls right in the receive filter's passband. Therefore, the transmit filter must attenuate this harmonic content to an acceptable level.

PHONE LINE INTERFACING

The phone line interfacing has to couple the Txcar onto the line while removing the Rxcar and channeling it to the receiver. Figure 14 shows a simple accoustical connection which uses the telephone's internal carbon microphone and speaker.

In this connection the telephone headset itself acts as the duplexer or 2 to 4 wire converter. Attenuation of Txcar to Rxcar should be infinite, but mechanical transmission or bleed through may occur and should be considered.

Typically accoustical coupling is only used for FSK type modems with low data rates, 1200 BPS and down. This is because of the poor quality carbon microphones found in most telephones.

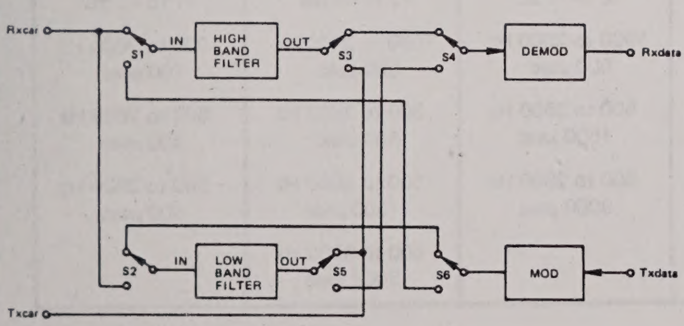

Figure 13: Mode Switching

The other coupling configuration is the direct connect, typically designed **DAA** (Direct Access Arrangements). The DAA, shown in Figure 15, serves to:

1. Provide DC isolation between modem and telephone line-T_1.
2. Provide a ring detect to control the on/off hook switch — may be manual.
3. Provide a DC current path during off — hook to "hold" the Line — L1. This current is monitored by the telephone company to indicate when someone is connected to the line.
4. Provide transient protection — R_1/Z_1

A hybrid transformer is often used in place of the differentially connected op amp to perform the duplexer function, shown in Figure 16.

The hybrid transformer, T_1, provides better Txcar bleed-through attenuation (typically 20 dB) but at additional expense over the op amp duplexer.

COMPLETE MODEM SPECIFICATIONS

Line signals received by the modem are often greatly changed by the media from the originally transmitted signal at the originating modem. With telephone communications Bell specifies five different lines which appear in standard dial-up lines as shown in Figure 17. Since which line will appear is totally unknown, the worst case line (Bell 3002) is generally used for modem evaluation.

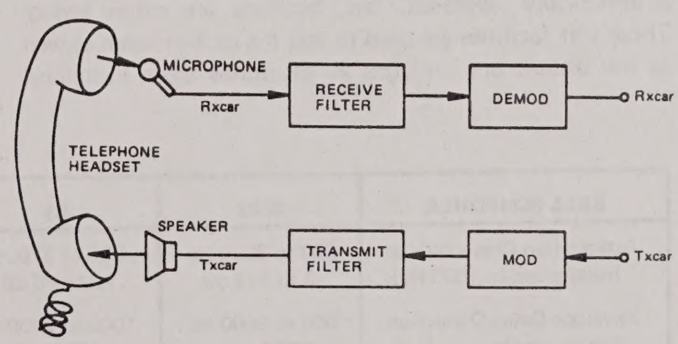

Figure 14: Accoustical Coupling

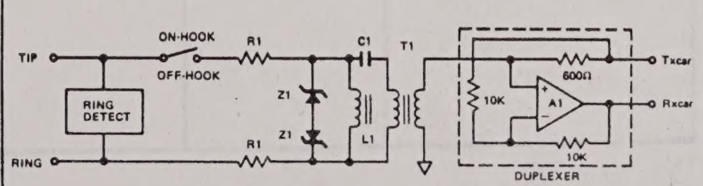

Figure 15

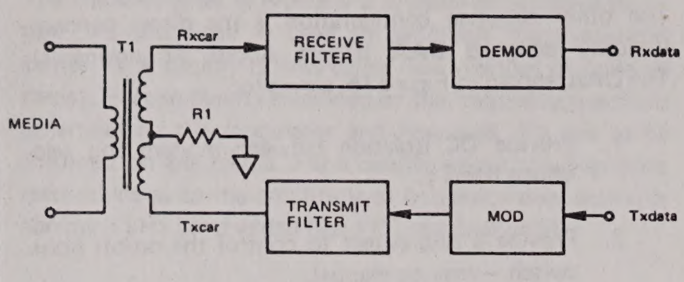

Figure 16

From Figure 17 it can be seen that severe amplitude variations can occur on received line signals. Typically modems should function with received line signals from 0 to -45 dBm (2.2 V to 12.3 mVp-p).

Group delay also can experience large changes. Figure 18 shows the general shape of the group delay characteristic as a function of frequency. Medium to high speed modems (PSK encoding) generally use some kind of equalization to compensate for group delay variations. The dotted line in Figure 18 illustrates a compromise line equalization to flatten the effective group delay variation.

Direct connection to the telephone line requires FCC approval as specified in Part 68 of the FCC regulations. One of the main requirements of this FCC regulation is the maximum in-band power levels over frequency bands not only within the 300 to 3000 Hz line bandwidth, but also above it be restricted to given levels. Figure 19 shows the maximum power levels to be put on the line.

Because modems communicate over vast distances, often automatically operated, test facilities are often added. These test facilities are used to test the local modem as well as the distant one. Figure 20 illustrates these functions.

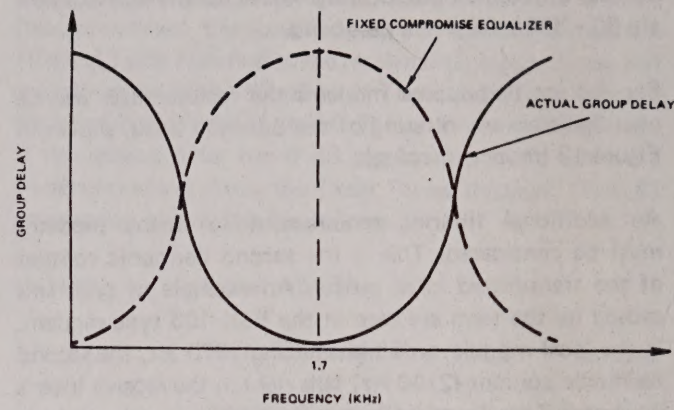

Figure 18: Group Delay Characteristics

Frequency (KHz)	3.995 to 4.005	4 to 10	10 to 25	25 to 40	Above 50
Maximum Power Level (dBm)	-18	-16	-24	-36	-50

Figure 19: FCC Phone Line Restrictions

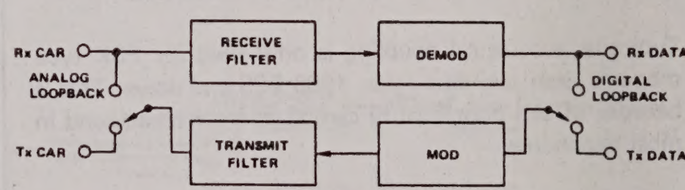

Figure 20: Test Facilities

BELL SCHEDULE	3002	C1	C2	C4	DCS-S#
Attenuation Characteristic (referenced to 1000 Hz)	300 to 3000 Hz -3 to +12 dB	300 to 2700 Hz -2 to +6 dB	300 to 3000 Hz -2 to +6 dB	300 to 3200 Hz -2 to +6 dB	300 to 3000 Hz -1 to +3 dB
Envelope Delay Distortion ((max, μsec)	800 to 2600 Hz 1750 μsec	1000 to 2400 Hz 1000 μsec	1000 to 2600 Hz 500 μsec	1000 to 2600 Hz 300 μsec	1000 to 2600 Hz 100 μsec
		800 to 2600 Hz 1750 μsec	600 to 2600 Hz 1500 μsec	800 to 2800 Hz 500 μsec	600 to 2600 Hz 300 μsec
			500 to 2800 Hz 3000 μsec	600 to 3000 Hz 1500 μsec	500 to 2800 Hz 600 μsec
				500 to 3000 Hz 3000 μsec	

Figure 17: Bell Dial-up Line Characteristics

XR PART NUMBER	FUNCTION	STANDARD	
		BELL	CCITT
XR-210	FSK Mod or Demod	103, 212A (FSK), 202, NS	V.21, V.23, NS
XR-2211	FSK Demod	103, 212A (FSK), 202, NS	V.21, V.23, NS
XR-2206	FSK Mod	103, 212A (FSK), NS	V.21, V.23, NS
XR-2207	FSK Mod	103, 212A (FSK), NS	V.21, V.23, NS
XR-14412	FSK Mod/Demod	103	V.21
XR-2123	PSK Mod/Demod	212A (PSK), 201	V.22, V.22, NS
XR-2124	FSK Mod/Demod/Filter	202 (1200 BPS Receive) (75 BPS Transmit)	V.23 (1200 BPS Receive) (75 BPS Transmit)
XR-2120	PSK/FSK Filter	212A, 103	V.22 (needs 1800 Hz notch)
XR-2103	FSK Filter	103	V.21

NS = Non Standard

EXAR PART CROSS REFERENCE TO MODEM TYPE